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A nexus approach for sustainable urban Energy-Water-Waste systems planning and operation

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ABSTRACT:

Energy, water and waste systems analyzed at a nexus level is key to move towards more sustainable cities. In this paper, the “resilience.io” platform is developed and applied to emphasize on waste-to-energy pathways, along with the water and energy sectors, aiming to develop waste treatment capacity and energy recovery with the lowest economic and environmental cost. Three categories of waste including wastewater (WW), municipal solid waste (MSW) and agriculture waste are tested as the feedstock for thermochemical treatment via incineration, gasification or pyrolysis for combined heat and power generation, or biological treatment such as anaerobic digestion (AD) and aerobic treatment. A case study is presented for Ghana in Sub-Saharan Africa, considering a combination of waste treatment technologies and infrastructure, depending on local characteristics for supply and demand. The results indicate that the biogas generated from waste treatment turns out to be a promising renewable energy source in the analyzed region, while more distributed energy resources can be integrated. A series of scenarios including the business-as-usual, base case, natural constrained, policy interventions and environmental and climate change impacts demonstrate how simulation with optimization models can provide new insights in the design of sustainable value chains, with particular emphasis on whole-system analysis and integration.

1. Introduction

With rapid urbanization, particularly in the developing world, cities are facing sustainability challenges on the nexus of energy, water and waste commensurate to financially feasible and reliable infrastructure systems planning.[1,2] The projected 50% increase in global population in 21st century will lead to 11.2 billion people by the end of this century.[3] This combined with the non-

OECD economic growth is expected to bring a 33% increase in energy demand globally by 2050.[4] Energy is the dominant contributor to Greenhouse Gas (GHG) emissions and waste-to-energy pathways have been identified by the IEA as one of the promising solutions for a low-carbon pathway towards the 2°C warming scenario.[5] Moreover, rising waste generation yields additional GHG contributions and other environmental impacts. For instance, one-third of food produced globally is lost or wasted every year, which is responsible for over 7% of the GHG emissions and the waste of 250 km^3 water (8.5% annual withdrawn).[6] The choice of waste-to-energy technologies, their deployment and logistics of which depend on local conditions including demands and availability of resources and associated networks, imply that a spatially explicit representation and computer-aided planning is imperative.[7] To support investments and operational decisions for sustainable infrastructure systems development in cities, systems modelling approaches can be deployed taking into account energy-water-waste cross-sectoral integration, spatial-temporal resource flows and allocation, long-term socio-economic and environmental targets as well as technical constraints from a whole systems perspective.[8–10] Our thorough literature review shows that previous research has been conducted in the energy supply-demand optimization and system analysis under a developing country context, e.g., energy system planning and forecasting, remote-area distributed renewable energy, bioenergy research optimization and waste-to-energy systems.[11–13] Applications in support of the energy-water-food nexus planning has become a central focus in the current research agenda of developing systematic modelling tools.[14–18] However, there is a significant gap on the decision-making tools bridging water-energy-waste sectors with supply-demand needs at both spatial and temporal scales, despite the fact that many tools have been developed and used effectively for individual domains.[19–21]

In this paper we present the application of an integrated decision-making tool based on the resilience.io platform, which provides a series of modules to allow forecasting of socio-demographic scenarios, simulating spatio-temporal activities, and planning investment and operational strategies to meet the Sustainable Development Goals (SDGs).[22] We developed the platform to study urban systems interactions through socio-economic forecasting, agent-based modeling, and resource-technology network optimization. The consensus among multiple sectors in decision making using these simulation and optimization tools has been effectively applied to the water-energy-food nexus in previous research to deliver both economic and environmental benefits.[23,24] By introducing life cycle sustainability assessment (LCSA) and optimization into the developed resilience.io platform, system-wide economic, environmental and social sustainability perspectives have been incorporated and bridged with supply and demand across multiple-sectors. LCSA addresses the overall sustainability impacts associated with infrastructure, individual sectors and their interrelationship, or the entire urban development plan from a cradle-to-grave perspective.[25] In combination with assessing policy support, such as a Feed-In Tariff (FIT) scheme (remunerating the sales of surplus electricity from technology operation back to the grid), our modelling tool incorporated green financial investment strategies to investigate the policy implications on the system performance.[26] In addition to the commonly existing centralized systems, decentralized technologies have also been incorporated into our model, where the application of a systematic optimization tool is of critical importance for transparent urban service systems planning.[27] A case study and scenario-based approaches demonstrate our model's applicability in a developing country context, where possible cross-sector solutions for water, energy, waste and food for Ghana were scrutinized.[28]

The capital city of Ghana and its neighboring administrative districts form the Greater Accra Metropolitan Area (GAMA). It is a rapidly growing metropolitan region, where great efforts have been placed to improve local community livelihood and city sustainable development particularly in the water sector. Household access to piped water grew by more than 80% from 2000 to 2010 and potable water provisioning has been improved dramatically in recent years. The city has seen large expansions of potable water treatment at the Kpone site north of the city-region (several hundreds of thousands m^3 per day), as well as the addition of a 60,000 m^3 per day desalination plant.[29,30] However, the percentage of total wastewater treatment (WWT) declined from around 10% to nearly zero between 2000 and 2010, whilst the population of GAMA grew from 3 to 4 million people. Nearly all untreated wastewater therefore is discharged to the environment. Minor improvements have been made by introducing a lagoon-based treatment plant with a capacity of 6,400 m^3 per day at the University of Ghana Legon and efforts are underway to rehabilitate the Jamestown treatment plant. Yet, these facilities are far from being adequate and the WWT sector in this region still faces significant challenges on system development and maintenance due to the financial constraints which conflict with the increasing environmental concerns.

A promising solution would be to recover the resources contained in the wastewater. Anaerobic digestion (AD) has been widely acknowledged as an effective technology for the energetic valorization of various organic feedstock which is not only constrained to the wastewater, but also applicable to organic solid wastes such as agro-industrial residuals and municipal solid waste.[31] AD can transform waste treatment from an energy consumer to a net producer due to a 2-4 times higher energy recovery from the waste than the AD operational demands.[32] The generated biogas, as one of the highlighted prioritized renewable fuels, has multiple applications, e.g. direct utilization for combined heat and power (CHP) generation as well as the ability to be upgraded and compressed as transport fuel. In fact, biogas has been recognized as a rising renewable energy source in both rural and urban areas of many African countries.[33] Such a combined production of heat, electricity and fertilizer provides a transitional scheme for local residents in Ghana. It can allow the mitigation of being heavily relied on burning traditional biomass and waste (e.g. firewood and charcoal) for household cooking and heating, which in turn has caused numerous environmental, health and safety concerns. Ghana has the potential to install a large number of biogas plants (54-865 MW installed capacity per year by estimation).[34]

To incorporate these renewable technologies into the waste treatment and energy generation process, policy regulations that provide energy market support would be required to promote waste recovery and further penetration of renewable sources. A tariff scheme, which has been generally acknowledged as an effective deployment policy internationally and could potentially be adopted in Ghana, has been modelled in our case study to explore the potential role of this governmental intervention scheme. The applicability of a whole-system decision support tool to the broader developing country context is successfully illustrated by the presented regional application.

The rest of the article is structured as follows. Section 2 first describes the overall life cycle approach, optimization formulation and associated models, followed by a detailed description of data input mechanisms. Section 3 mainly demonstrates how the overall methodology is applied to a Sub-Saharan African city-region to achieve cost-optimal and sustainable development plans especially in the water, energy and waste treatment sectors. A series of scenarios are analyzed including the “business-as-usual”, “base case”, “natural constrained”, “policy interventions” and “GHG reduction” related.

2. Methods

We developed the resilience.io platform initially for integrated resource planning, which mainly addresses water and energy, as well as their nexus.[22] It is of paramount importance to connect the waste treatment especially waste-to-energy pathways to these utilities. In this work, only electricity is studied as the representative energy product, while heat and fuel are not included in the supply-demand forces, but only analyzed as additional output of the energy sector to the economy. The ultimate goal is to develop the treatment capacity and energy recovery with the lowest economic and environmental costs.

2.1 General framework

The overall modelling framework and data flows are illustrated in Figure 1, where three key components are soft-linked via data feedback loops including the resilience.io platform, optimization and LCSA. LCSA is an evaluation tool accounting for three sustainability pillars i.e. life cycle environmental assessment (LCA), life cycle costing (LCC) and life cycle social assessment (S-LCA).

The resilience.io platform incorporates a series of modules to perform forecasting of socio-demographic scenarios, simulation of spatial-temporal supply/demand profiles and planning investment and operational strategies to meet the SDGs for multiple sectors including water, energy, food and waste. For the urban region under investigation, a comprehensive database with respect to the current resource availability, waste treatment capacity and distribution is built based on national and local statistics. Key references include household water use,[35] total water use and treatment capacity,[36] waste-water treatment plants,[37] new infrastructure projects,[38], and household infrastructure access.[39] More exhaustive cleaned and referenced datasets for these aspects have been deposited on the openAfrica data portal.[40] The spatially explicit waste generation and resource demands are projected by using agent-based models embedded in the resilience.io platform. The behaviours of diverse population groups are captured, which are categorized by their geographical district (original and real-time in the agent-based simulation), age, gender, work force, income rank and access to infrastructure. The overall sustainability footprints of technologies and the whole socio-technical system have been evaluated using LCSA inclusive of social (e.g., job creation, gender equality), economic (including capital costs, operating and maintenance costs) and environmental (e.g., climate change) aspects. The module that optimizes the resource technology network uses the current pre-allocated infrastructure (existing on-the-ground technologies), as per above and described in the deposited openAfrica data for initialization.[40] This module incorporates novel technologies for waste resource recovery taking into account land-use (e.g., land types and available area) and fiscal budget (e.g., as a maximum cap of total costs or relaxed to obtain the optimal planning) constraints, with an objective to minimize the system-wide economic and environmental costs. The results provide development plans for alternative technologies, infrastructure as well as production and transportation schedule in order to meet the SDGs.

2.2 Optimization model structure

The interrelationship between water, waste and energy systems is addressed through material and energy balances. The main optimization problem is formulated as a mixed-integer linear programming (MILP) problem, with a multi-objective function which accounts for capital expenditures (CAPEX), operating expenditures (OPEX), and environmental impacts (mainly GHG emissions, monetized by carbon trading prices). The additional environmental costs associated with the nexus, such as the impact on air quality, human health and ecosystem quality, are obtained from the life cycle impact analysis as part of the results, instead of directly being included as a cost function term in the objective function. The objective function as shown in Eq. (1) combines weighing factors (*Wf*) and metrics (*m*) including costs for investment (*VIJ*), O&M (*VPJ*), resource transportation (*VQ*), pipe and grid expansions (*VY*) and resource import costs (*VI*) with details given in Eq. (2). All spatial districts are represented by *i*, technology by *j*, resource by *r*, metric by *m* and time scale by *t* (minor time periods, e.g., hours in a day) and *tm* (major time periods, e.g., years). The detailed explanation of the variables, parameters and models can be found in the Supplementary Information (SI).

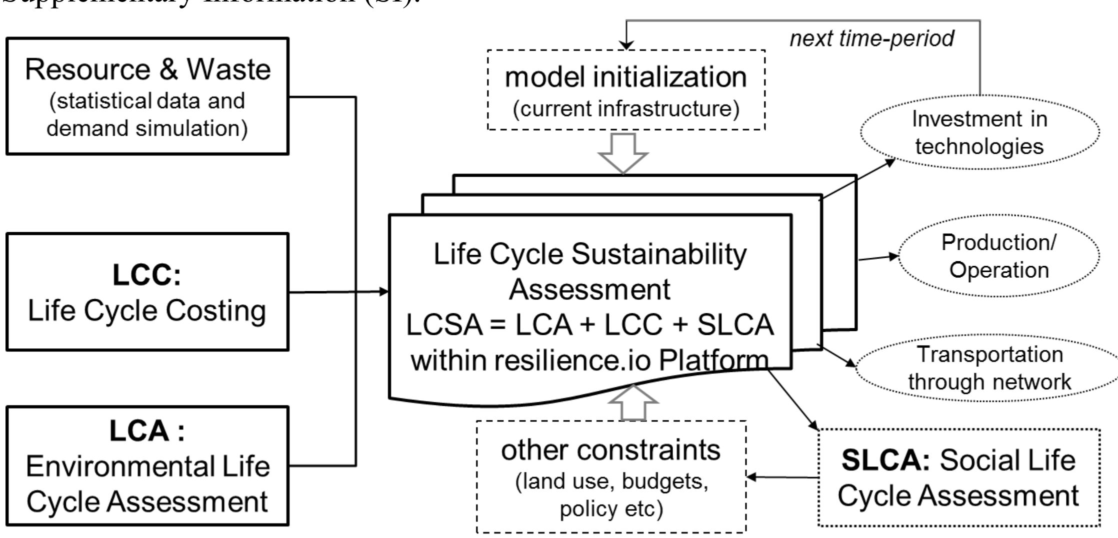


Figure 1. Overall methodology for analysis of urban waste and energy sectors using decision support platform through Life Cycle Sustainability Assessment.

Multiple waste streams are incorporated in the model including WW, MSW especially its organic fraction (OFMSW), and lignocellulosic agricultural waste (e.g., accumulated at plantations for treatment and energy recovery). Their geological distribution lays the foundation of quantifying the energy potential to be recovered through several pathways as per the superstructure diagram shown in Figure 2. Compared with traditional landfills or incineration to treat solid waste, catalytic thermal treatment (e.g., pyrolysis or gasification) or biochemical treatment (e.g., anaerobic digestion and aerobic process) can be promising avenue to recover energy from OFMSW in the form of heat and electricity. Meanwhile wastewater is often treated through chemical and aerobic processes or through anaerobic digestion, yielding a source of biogas for electricity or heating. Specifically, agricultural waste serves as a valuable resource for energy recovery via anaerobic digestion pathway.

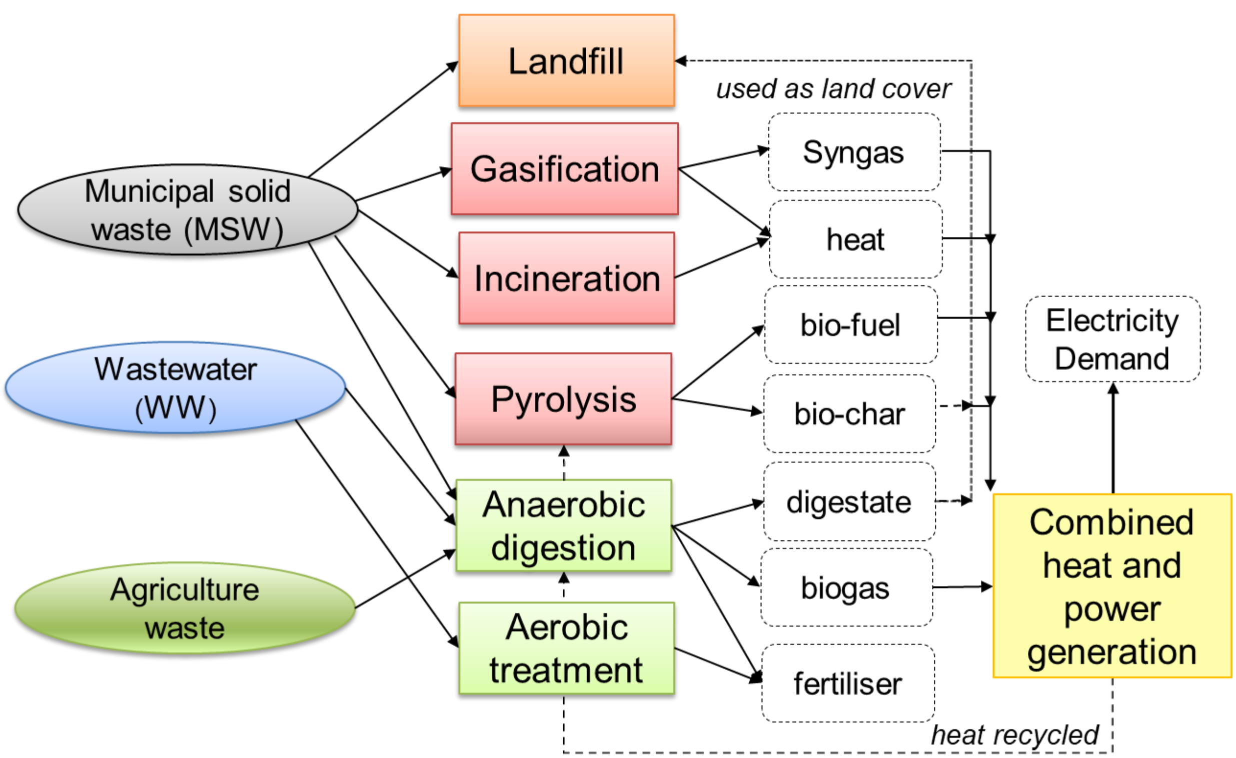


Figure 2. A superstructure diagram of waste and energy resource flows through multiple technologies.

$$Z = \sum_m Wf\ (m, tm)\, M(m, tm) \quad (1)$$

Where *Wf (m,tm)* and *M(m,tm)* represent the weighting factors and value for all metrics *m* evaluated in the objective function during time period *tm* respectively.

$$\begin{aligned} VM\ (m, tm) = &\sum_j \sum_i VIJ(j, i, m)\, INV(j, i, m) \\ &+ \sum_j \sum_i \sum_t VPJ(j, i, t, m)\, P(j, i, t, tm) \\ &+ \sum_{i,i'} \sum_r \sum_t VQ(r, t, m)\, dist(i, i')\, Q(r, i, i', t, tm) \\ &+ \sum_{i,i'} \sum_r VY(r, m)\, dist(i, i')\, Y(r, i, i', tm) \\ &+ \sum_i \sum_r \sum_t VI(r, t, m)\, IM(r, i, t, tm) \quad (2) \end{aligned}$$

The optimization model implements a set of constraints to drive the system in satisfying the respective waste treatment needs and electricity demand. First, equality constraints were introduced to achieve mass and energy balances at each level for every technology at all spatial zones and during each time period. Secondly, available operable capacities for each technology determine the upper limits for operations. Flow limits based on pipe, transportation network and grid connections are also imposed, which are defined by the associated geometric distance in kilometers (km). Finally, the investment allowance provides an upper bound of the total allowed cost for further infrastructure expansion. Besides the present steady-state system planning, future conditions are also predicted and planned through the forecasting models accounting for key parameters, such as the evolution of the population, income, and employment status. The optimization problem was solved using the open-source GNU Linear Programming Kit (GLPK), as the default solver freely available for the published platform, to allow an expanded access on the user-side.

2.3 LCSA and data input

The ‘cradle-to-grave’ LCSA approach generalized as Eq. (3) has been adopted to evaluate the sustainability footprints of waste treatment and recovery, including gasification, pyrolysis, incineration and anaerobic digestion. The mid-point characterization approaches were adopted in the LCSA evaluation, e.g. CML baseline[41] for LCA; cost-sub categories (e.g. operational cost, capital cost, labor costs) for LCC analyses[42]. As summarized in Table 1, the capital inputs and operation are modeled within the defined LCA system boundary based on the functional unit ‘per day operation for treating WW and/or bio-solid waste (including OFMSW and agricultural waste)’. An economic allocation is applied to the processes with multiple products, thus zero impacts caused by the upstream waste-generating process have been assigned to WW and OFMSW (by-products). A stoichiometric carbon-counting approach was used to ‘track’ the carbon flows from embedded carbon in waste chemical components (including carbon ‘sequestration’ into the agricultural waste at crop growth stage) and through waste treatment and recovery, as well as the release of carbon during anaerobic digestion and combustion.

The spatially-explicit agricultural land use maps of the studied region were derived from statistical reports and academic studies[27,43–45] which combined the biomass partitioning ratio, leading to an estimated distribution of agricultural lingocellulosic waste. These include the above-ground lignocellulosic residual fractions of cassava, maize and banana plants. Existing waste treatment facilities and future demographic changes were also derived from multiple published data sources.[46–50] The empirical data was used in the LCSA evaluation of organic waste treatment and recovery (i.e. gasification, pyrolysis, incineration) based on the operation and capital input-output flows generated from the WRATE (Waste Resources Assessment Toolkit for the Environment generated by Golder Associates) model and empirical and operational data derived from a UK commercial AD plant.[51] Data for other existing or potential technologies for electrical power sector such as hydroelectric, natural gas, coal and renewables (mainly PV and wind) were obtained from a combination of national reports and local data collection (see details in our previous work and references [52,53]). Further process descriptions and data flows are detailed in the SI.

Economic costs are analyzed through empirical process models with respect to input-output data of materials, feedstock, utilities and other consumed resources. The economic and social costs are then obtained through life cycle costing based on engineering estimation methods for each technology according to its characteristics. Table 1 provides an overview of environmental and economic performance in the waste treatment, especially waste-to-energy applications as an example. More information about the general energy sector including hydroelectric, fossil fuels and renewable energy generation can be found in the SI.

$$EI_{kpi} = \sum_{r}\sum_{s} EIf_{r,kpi}^{in} X_{r,s}^{in} + \sum_{c}\sum_{s} EIf_{c,kpi}^{out} X_{c,s}^{out} \qquad (3)$$

Where the variable EI_{kpi} denotes the total sustainability impacts of a given waste treatment and recovery process (per functional unit) expressed as Key Performance Indicator *kpi* (e.g. cost and GHG). EI_{kpi} is determined by the characterisation impact factors for input resource r ($EIf_{r,kpi}^{in}$) or emitted compound c ($EIf_{c,kpi}^{out}$) and the input or output flows ($X_{r,s}^{in}$ or $X_{c,s}^{out}$) at a life cycle stage s.

The uncertainty analysis toolbox for LCSA is available under the integrated modelling framework, but exceeding the spectrum of the current scope. Under our uncertainty analysis tool, statistical methods (maximum likelihood estimation and goodness of fit) and expert judgement based approach (pedigree matrix) have been developed to quantify the inventory uncertainties due to cumulative effects of data variability or inventory uncertainties. At LCSA impact assessment level, a Monte Carlo simulation approach is introduced to estimate the uncertainties in characterised results introduced by the statistical variability or temporal, geographical and technology gaps in the inventory data. Such methodology functions can greatly amplify the confidence in the research findings and provide more robust and tangible evidence in the support of optimal decision-making. However, uncertainty analyses are not demonstrated in this paper but will be investigated in follow-up studies.

Table 1 Model configuration for waste treatment and recovery technologies

<table>
<tr><th>Treatment technology [a]</th><th>Waste streams (Input)</th><th>Life span [a]</th><th>Technology description [a]</th><th colspan="2">Key operational parameter [a]</th></tr>
<tr><td>Incineration</td><td>OFMSW</td><td>25-year</td><td>Large-scale moving grate incinerator</td><td colspan="2">Efficiency=19% [b]</td></tr>
<tr><td>Gasification</td><td>OFMSW</td><td>25-year</td><td>Grate gasification</td><td colspan="2">Efficiency= 18.8% [b]</td></tr>
<tr><td>Pyrolysis</td><td>OFMSW</td><td>25-year</td><td>Twin rotary kiln pyrolysis</td><td colspan="2">Efficiency=13.3% [b]</td></tr>
<tr><td rowspan="6">Large-scale AD</td><td>WW</td><td rowspan="6">20-year</td><td rowspan="6">Continuous feeding thermophilic two-step digestion</td><td rowspan="6">Efficiency= 17.2% [b] OLR for WW= 3.2 kg COD/m^3/day [c] OLR for solid waste = 6 kg COD/m^3/day [c]</td><td>Biogas 94% COD conversion [d]</td></tr>
<tr><td>OFMSW and WW</td><td rowspan="2">Biogas -86% COD conversion [d]</td></tr>
<tr><td>OFMSW</td></tr>
<tr><td>Corn Stover</td><td rowspan="3">Literature-based biogas estimation [e]</td></tr>
<tr><td>Cassava leaf</td></tr>
<tr><td>Banana leaf</td></tr>
<tr><td rowspan="4">Small-scale AD</td><td>OFMSW</td><td rowspan="4">15-year</td><td rowspan="4">Small-scale single step digestion</td><td rowspan="4">Efficiency= 18.7% [b] OLR=6 kg COD/m^3/day [c]</td><td>Biogas: 86% COD conversion [d]</td></tr>
<tr><td>Banana leaf</td><td rowspan="3">Literature-based biogas estimation [e]</td></tr>
<tr><td>Corn stover</td></tr>
<tr><td>Cassava leaf</td></tr>
</table>

a. The representative AD and thermochemical pathways were modelled based on the operation and capital input-output flows generated from WRATE model and empirical and operational data derived from a UK commercial AD plant.[54,55]
b. Efficiency refers to the surplus electricity and heat generated and exported to grids from waste energy recovery. In incineration, on-site operation and transformation loss account for 22.1% electricity generated. Electrical conversion efficiency in AD is 20.35% with 15.7% and 8.1% of the generated electrical power consumed to operate large-scale and small-scale AD respectively.[54,55]
c. Organic loading rate (OLR) is measured in terms of the chemical oxygen demand (COD) of feed to a unit volume of digester per unit time[56];. ORL of 3.17 kg COD/m^3/day and 6 kg COD/m^3/day was

assumed for WWT and AD co-digestion (refer to co-digestion of wastewater and organic solid waste) , respectively.[57,58]

d. The COD removal efficiency for WWT and AD co-digestion was assumed as 99% (94% converted to biogas, 5% to cell mass) and 91% (86% converted to biogas, 5% to cell mass) respectively.[54,55]
e. The biogas production potential were estimated based on the empirical work on AD of lignocellulosic biomass as well as the representative data obtained from literature on chemical composition and characterisation of different waste streams in Ghana. [47,49,57–60]

3. Scenarios analysis and results

The Greater Accra Metropolitan Area (GAMA) in Ghana, which has a large potential for energy recovery from waste, is studied here for its optimal development strategies. The model aims to satisfy waste treatment needs and electric power consumption for the region divided into sixteen functioning zones. We first forecast the required demand from base year 2010 until 2030 and benchmark it with statistical reports. A series of scenarios including "business-as-usual", "base case", "resource constrained", "policy interventions" and "GHG reduction" are analyzed sequentially.

3.1 Business-as-usual and base case scenarios

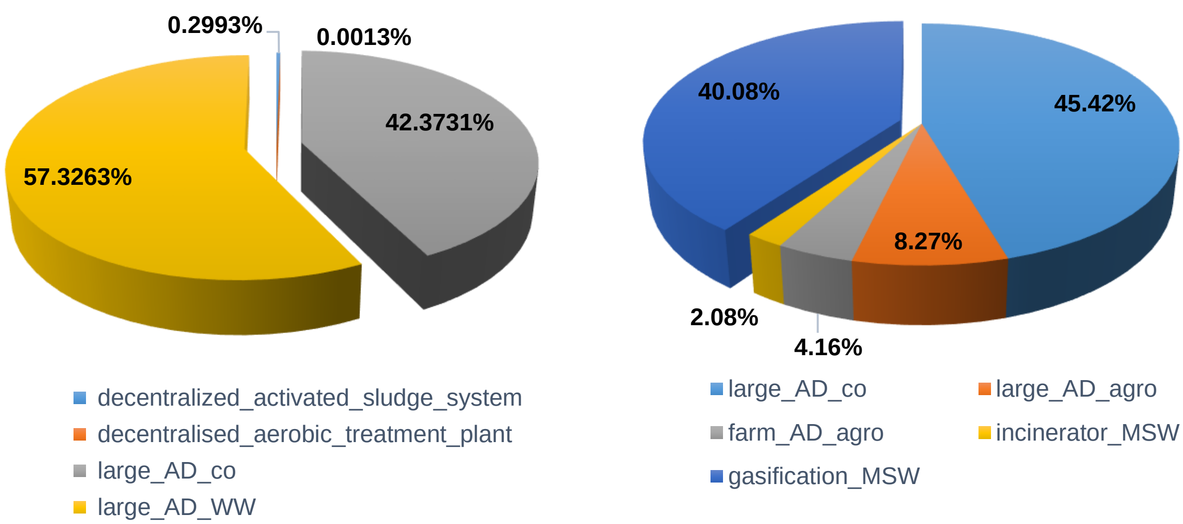
A total of seven wastewater treatment methods, six municipal solid waste (including WW and MSW co-digestion) and two agro-waste treatment technologies for three locally common agricultural products (banana, cassava, and corn) were analyzed with respect to waste-to-energy pathways. An additional set of thirteen power generation technologies which are existing or promising to be utilized in Ghana are also accounted for in the case study to evaluate how energy recovered from waste fits within the entire power system.

In a *business-as-usual* scenario, the existing infrastructure has little capacity to treat wastewater and MSW and only 63% of total citizens' electricity demand satisfied. Therefore, the resilience.io model can largely contribute in providing an optimized investment and operations plan for all potential and existing technologies which in return minimizes the total system cost.

By investing on the available array of technologies, the municipal facilities can gradually meet all citizens' essential requirements and gradually reach each SDG by 2030. The CAPEX investment to meet this goal was estimated around 16.87 billion USD for the GAMA region's waste treatment and power sector, excluding sunk investments in existing units evaluated in the base year (2010), while the yearly OPEX by 2030 is estimated at 439.0 million with an associated 22.12 million metric tonnes CO_2 equivalent GHG emissions. It is evident from the results that large-scale anaerobic digestion is a more effective solution among all wastewater treatment approaches, while gasification and large-scale anaerobic co-digestion are suggested for MSW treatment. Combined Cycle Gas Turbines (CCGT) and onshore wind energy conversion systems have dominant advantages among power supply technologies due to their relatively low costs, accounting 63% and 33% of total power supply respectively. However, the adoption of power facilities is limited by the availability of fuel sources and renewable energy potential, especially for large-scale application, which makes the "*base case*" optimized plan rarely feasible in real-world conditions. To obtain a more realistic development plan, location and resource-specific constraints are added when generating the investment and operation strategies, so that the environment variability is appropriately accounted for.

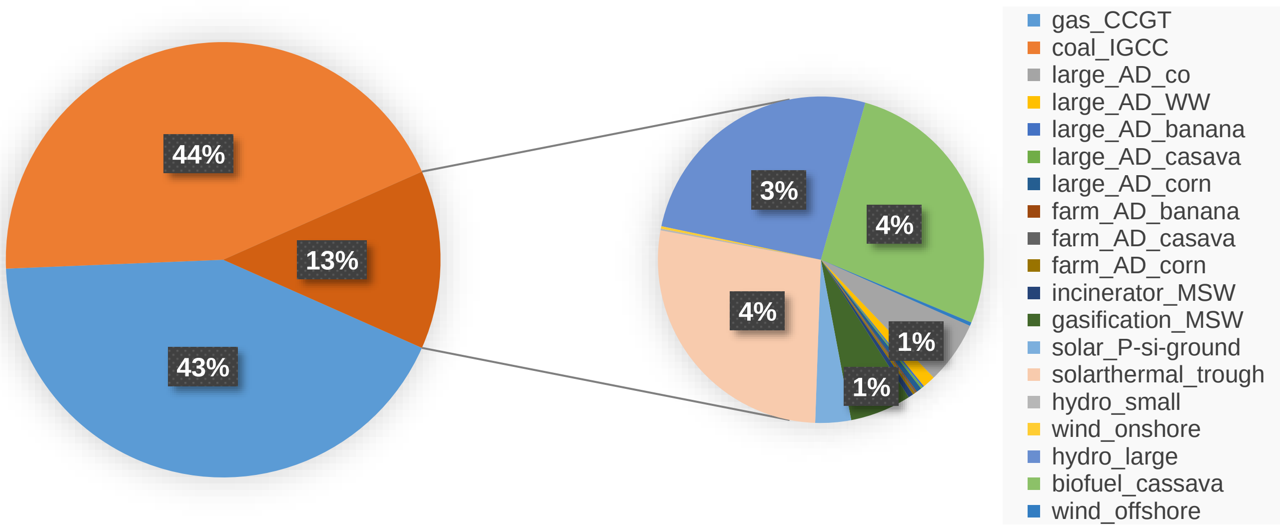
3.2 Scenarios with natural resources constraints

In the following scenario of resource constrained planning, land and resource constraints are imposed to suggest a localized technology selection. For example, the extensive land use of wind energy conversion systems and water bodies for large hydro plants are not available in most regions and agricultural conditions render significant regional differences. Accounting for these realistic factors, the results indicate a bio-economy scenario in which agro-wastes are fully utilized for energy recovery. Both large and farm-scale anaerobic digestion is preferable in all cases with benefits of energy recovery from waste. A combination of gasification and incineration (solid waste), large-scale AD (WW and OFMSW co-digestion, agro-waste digestion), and farm-scale AD (agro-waste) provides waste treatment strategies at the lowest cost. Figure 3 below gives an overview of the most financially efficient technology mix with respect to dispatched capacities that fulfil the total power demand. The minimized cost for a resource constraint scenario is higher than the base case, with CAPEX requiring 34.91 billion USD over 20 years; annual OPEX was found to be 516.9 million with all infrastructure in place, which is equivalent to 79.6 USD per capita for the whole waste treatment and power sectors and coupled with 54.95 million metric tonnes CO_2 equivalence.



(a) Model suggested wastewater treatment technologies (by wastewater handling capacity).

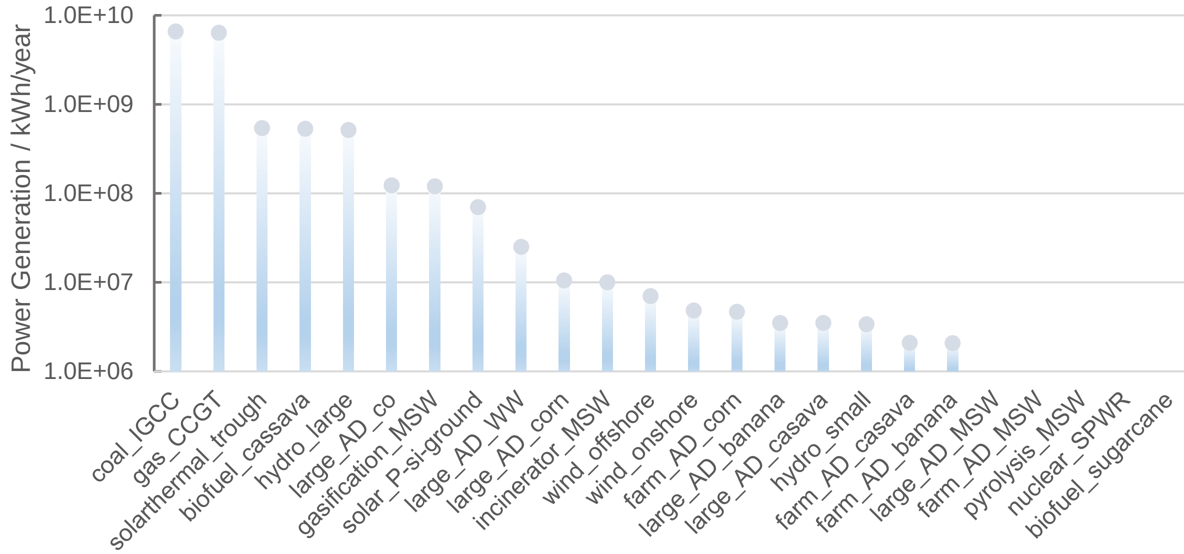
(b) Model suggested municipal solid waste and agro-wastes treatment technologies (by solid waste handling capacity).



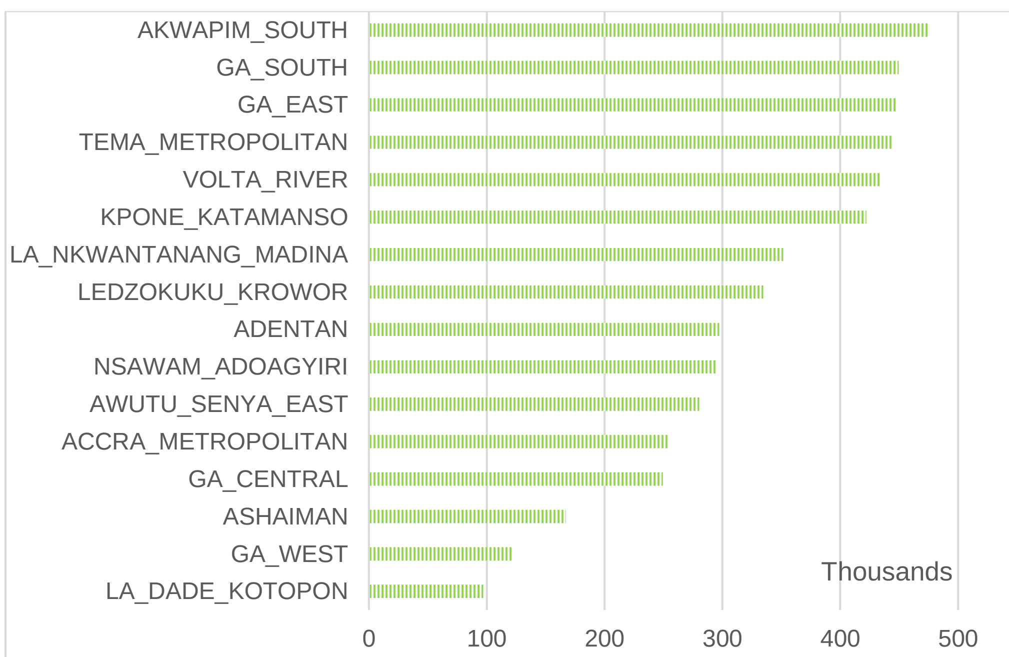
(c) Optimal power supply technologies (by generation capacity).

Figure 3. Technology mix with minimal costs for meeting SDG goals in 2030 (scenario with natural resources constraints).

The results suggested that the large-scale anaerobic digestion is the preferred solution among all wastewater treatment routes, while gasification and large-scale anaerobic co-digestion are suggested for MSW treatment. To have an in-depth understanding of the life-cycle performance of the obtained technology landscape, Figure 4(a) further demonstrates the energy generation from multiple waste-to-energy pathways, plus commonly exploited fossil fuel and renewable energy generation plants for GAMA in 2030. It is obvious that fossil fuels still play a main role in energy provision; this can be explained by the cost advantages of Coal Integrated Gasification Combined Cycle (IGCC) and Gas CCGT over other power supply technologies despite their carbon-intensive nature (Figure 4(a)). Additionally, as a key metric in the social LCA, labor hours required to operate the waste treatment and power utility infrastructure imply the creation of 2,134 full-time job per year (Figure 4(b)).



(a) Power generation per year of selected power generation technologies.



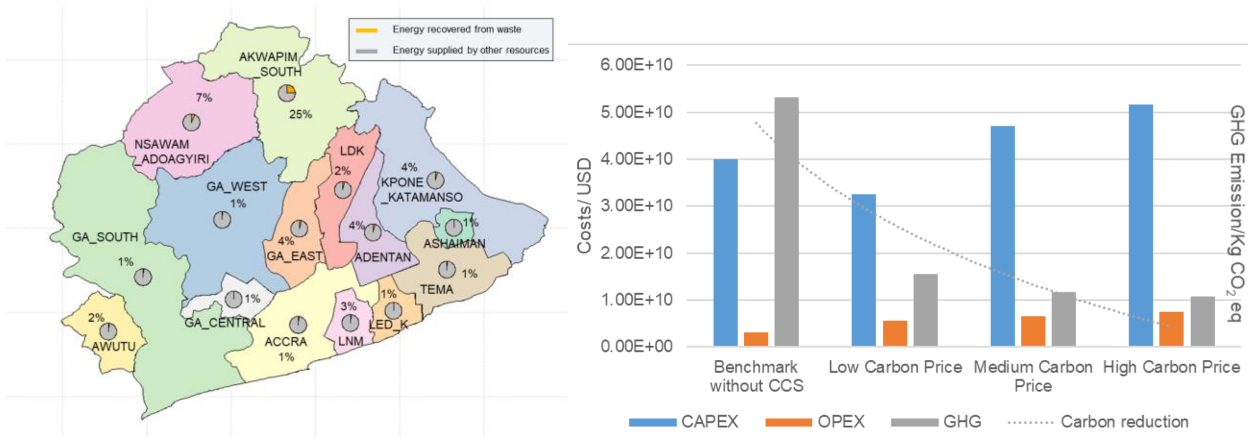
(b) Labor needs (hours equivalent per year) in each studied region in GAMA from waste and energy sectors.

Figure 4. Model suggested capacities and production rates per year for technologies in 2030 (scenario with natural resources constraints).

3.3 Scenarios with policy interventions

The previous section illustrated how spatial constraints of natural resources can potentially affect investment allocation. Additionally, decision makers also face political challenges or the need to take into account other key considerations outside the model's scope, for instance to implement interventions which encourage, penalize or even ban certain technologies. The materialized approach adds flexibility to the users in imposing user-based interventions and obtain an optimized plan within the frame of these user-defined conditions.

As a commonly adopted policy intervention in the energy sector, a feed-in tariff is taken as an example, which allows surplus power generation to be sold back to the grid. This provides advantageous prices depending on different sources, so as to encourage higher penetration of renewable sources in the overall electricity supply scheme. Local feed-in rates for wind, solar, hydro and gas, recovered from wastes and biomass, were obtained from the Ghanaian domestic Public Utilities Regulatory Commission (PURC). The results of a scenario with these tariffs are shown in Figure 5(a) below and demonstrate how government enforced incentives can promote clean energy technologies to boost the waste-to-energy utilization. With the same capital investment, operational costs are significantly reduced mainly due to a selection of different technologies benefiting from the feed-in-tariffs. Only 24.3 USD per capita per year of OPEX is required to satisfy all waste treatment and energy demand, which is a 69.5% reduction when compared with the OPEX of 79.6 USD in the previous case (no FIT set). The map gives an overview of the studied region with the pie charts denoting the proportion of energy recovered from local waste sources including WW, MSW and agro-waste in the total electricity supply from the optimized results, for the SDG target year of 2030. The other suggested investment strategies and operation plans for each region are returned by the model from 2010 to 2030, where the SDGs are expected to be gradually met.



(a) Waste-to-Energy penetration by district (with FIT).

(b) Economic and environmental performance with different carbon price and enabled CCS technology.

Figure 5. Performance indicators of the whole waste and energy systems to satisfy total demand in year 2030 (scenarios with policy interventions through FIT and carbon price).

3.4 Scenarios with environmental and climate change impacts

In this scenario, we specifically focus on the climate change impacts from a life cycle perspective. When the carbon trading price increases (especially to multiples of the current level of 12.5 USD per metric tonnes carbon) the overall dominant weighting of GHG emissions becomes more significant in the total cost. This leads the energy sector towards a low-carbon transition. Although it comprises a certain amount of economic benefits, long-term sustainability is witnessed especially when coupled with novel technology selection. For example, advanced carbon capture and storage (CCS) technologies can be introduced as an option to partly substitute traditional fossil fuel plants for cleaner energy supply, instead of fully switching to renewable resources. The cost therefore does not obtain a significant increment (less than 18%), while the CO_2 equivalent GHG emissions can be reduced by more than 70.9% when compared with the scenarios without CCS facilities. A total of 1,749 jobs is required to operate the infrastructure in all the studied sectors. Figure 5(b) further compares each cost category under the scenarios of low, medium and high carbon prices, indicating that the costs of decarbonisation are modest, with additional job creation being beneficial for the whole society. From a local government's perspective currently the costs cannot be fully met domestically. This is due to the fact that the annual government budget for the entire country fluctuates around 7 billion USD. The solutions could be rendered feasible if carbon trading pricing is introduced at a level that provides sufficient returns for investors. This would enable international capital investment to become more attractive in low carbon infrastructure projects supporting waste-water-energy-land nexus.

4. Discussions

The development of waste-to-energy pathways brings substantial benefits to reduce GHG emissions with improved resource allocation efficiency. Through a comprehensive LCSA, the materials, energy, economic, environment and social impacts of a system can be evaluated successfully. As a summary, we have presented a holistic approach to provide decision support for urban waste treatment and power supply. The demand data is obtained by statistical sources and agent-based simulation by formulating a system in which people, infrastructure and technologies interact in a reciprocal relationship with the surrounding environment. The resource-technology-network optimization model further evaluates available resources and returns the optimal development/investment strategies under the given set of constraints, as explored in the respective scenarios.

The distinct optimal strategies emerged by varying policy (e.g., FIT) and technology options (e.g., land constraints, CCS), with substantial implications for overall technology systems and the extent of waste-to-energy integration, as well as CAPEX and OPEX levels to SDG targets on water, wastewaters and energy. Land constraints resulted in a reduction of gas CCGT and shift from onshore wind to coal IGCC capacity and increased large-scale AD of crop residues and MSW, at double the CAPEX and 17% more OPEX. By imposing a FIT to support waste utilization for energy, previously marginal sources can be efficiently converted, providing a growth of share in electricity generation, with a 70% reduction in OPEX. When the advanced CCS and a high carbon price (125 USD/ton CO_2) areintroduced, GHG emissions reductions of 70% can be achieved at a manageable increase level of CAPEX (18%). The interaction between policies and technology that emerges in the wastewater and energy sectors shows that distributed energy generation technologies and waste-circular systems can be integrated. Water flows and wastewater treatment sector have been formulated in the optimization model, contributing to the objective functions. The optimization model presented in this study can be further expanded to address other water-related issues such as the consumption of different categories of water and aquatic system quality degradation (e.g. eutrophication, freshwater toxicity). This may lead to significant shift in the optimal solutions e.g. coal-driven technologies, which may appear to be less competitive if considering their water quality degradation profiles. Being able to address such cross-domain interactions and focusing on the whole system or nexus level is one of the main advantages of the presented approach herein.

As the Government of Ghana is currently elaborating on a long-term national development plan to steer the country through the next 40 years, the platform shows clear evidence of benefits for decision makers through our local dissemination events. Various government interventions can be studied in the model, such as carbon trading prices in collaboration with international agencies, clean energy technology incentives by local governments, and most importantly satisfying demand targets to achieve the sustainable development goals. Bio-renewable energy recovered from waste treatment using anaerobic digestion was shown to be one of the most promising sustainable energy source options in the studied region. The process serves as a reliable method to treat waste while the digested sludge can be used as soil fertilizer or landfill cover. To implement such technologies, it is necessary to tailor the policy measures and technology integration with local and international support mechanisms. Capital expenditures for infrastructure in the GAMA context are borne partially by dedicated national governmental funds for regions and via international loans. Novel instruments for developing countries, such as the Green Climate Fund, can support the incremental capital cost that emerged as part of a loan package, to ensure that novel infrastructure is climate proof. Equally important is the demonstrated reduction in OPEX as this needs to be sustainable locally from energy and water utility revenues, with the respective increase in job creation to support such payments.

This study has set up an example for systematic resource nexus analysis for developing countries/regions to leverage global development. Future work will explore a broader range of waste-to-energy technologies and apply the presented methodology to other city regions. The detailed investigation of various CCS and clean energy technologies and their broader environmental impacts associated with costs of disposal and environmental remediation are out of the current research scope and is part of our future work plans. We will also analyze additional scenarios, such as different tariff and incentive settings applied to electricity derived from different feedstocks across multiple regions, resilient adaptions to changes of natural environment, international investment, regulations and roadmap for clean energy transitions.

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Supporting Information Available including:

Part A: Input parameters, Part B: Model details and Part C: Parameters and results of each scenario. This information is available free of charge via the Internet at http://pubs.acs.org

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